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Short Intense Bursts in Magmatic Activity in the South of Siberian Platform (Angara-Taseeva Depression): the Paleomagnetic Evidence

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Abstract—Based on the paleomagnetic study of intrusive and explosive Permian-Triassic traps in the Angara River basin, Siberian Platform, it is established that the formation of the traps was marked by three short and highly intense bursts in magmatic activity, which resulted in the intrusion of three large dolerite sills (Tolstomysovsky, Padunsky and Tulunsky) and the deposition of the tuffs of the Kapaevsky Formation. These magmatic bursts occurred against the long-lived less intense background magmatism, which caused the formation of small intrusive bodies and tuff sequences. The geochronological data and correlation of the Angara traps to the effusive trap sequences in the north of the Siberian Platform (Norilsk and Maymecha-Kotuy regions) indicate that intrusion of the Tolstomysovsky sill and eruption of its comagmatic tuffs of the Kapaevsky Formation occurred in the Early Triassic. The obtained paleomagnetic data contradict the existing idea that the Padunsky and Tulunsky sills are coeval. Moreover, these data show that the magmatic bodies of different ages were mistakenly referred to the same sill.

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INTRODUCTION

The Siberian Trap Province is believed to be the largest area that experienced intraplate basaltic magmatism in Phanerozoic (Vasil'ev et al., 2000; Nikishin, 2000). The present interest in the Siberian traps is associated with the identification of the probable cause-effect relationship between the eruption of huge volumes of volcanic material and the catastrophic mass extinction of species at the Permian-Triassic boundary (Courtillot and Olson, 2007). Considering the existing estimates of the volume of trap volcanic products (2–5 million cubic kilometers according to (Vasil'ev et al., 2000; Fedorenko et al., 1996)) and the duration of the volcanic activity (1–2 Ma according to (Kamo et al., 2003, Renne and Basu, 1991)), the average rate of eruption in the case of uniform trap formation was at most 5 cubic km per year. This value does not exceed the volume of the basalts that erupted annually in the mid-ocean ridges (Davies, 1999) and therefore it is insufficient to have caused the biospheric catastrophe. However, by the example of the Deccan traps it was shown recently that trap volcanism could have occurred in the form of short intense bursts separated by quiet periods having a longer duration (Chenet et al., 2008). In the case of short intense magmatic pulses, a catastrophic environmental aftermath is probable. The similar character of the magmatic activity was established for the Norilsk and Maymecha-Kotuy regions in the north of the Siberian Trap Province (Pavlov et al., 2011). The volcanic pulses in these works were identified by the paleomagnetic method, which provides a more detailed view of the volcanic sections than the isotope-geochronological methods. We applied this method for estimating the intensity of the Permo-Triassic magmatism in the south of the Siberian Platform. The results of our study are presented in this paper.

GEOLOGICAL OVERVIEW

In the southern part of the Siberian Platform, the Permian-Triassic traps span the Angara-Taseeva Basin and the Irkutsk amphitheater (Fig. 1). In the north, there is the flat wall of the Tunguska syncline, where the Permian-Triassic volcanic products are represented by tuffs, tuffites, and tuff sandstones reflecting the initial stages in the magmatic activity (Domyshev, 1974). The southern margin of the volcanogenic-sedimentary formations of the Tunguska syncline is located in the middle reaches of the Angara River. Tuffaceous sediments are represented here by basaltic tuffs, tuffites, and volcanogenic-sedimentary rocks (tuff sandstones and tuff siltstones), which were initially referred to the Lower Triassic Korvunchansky

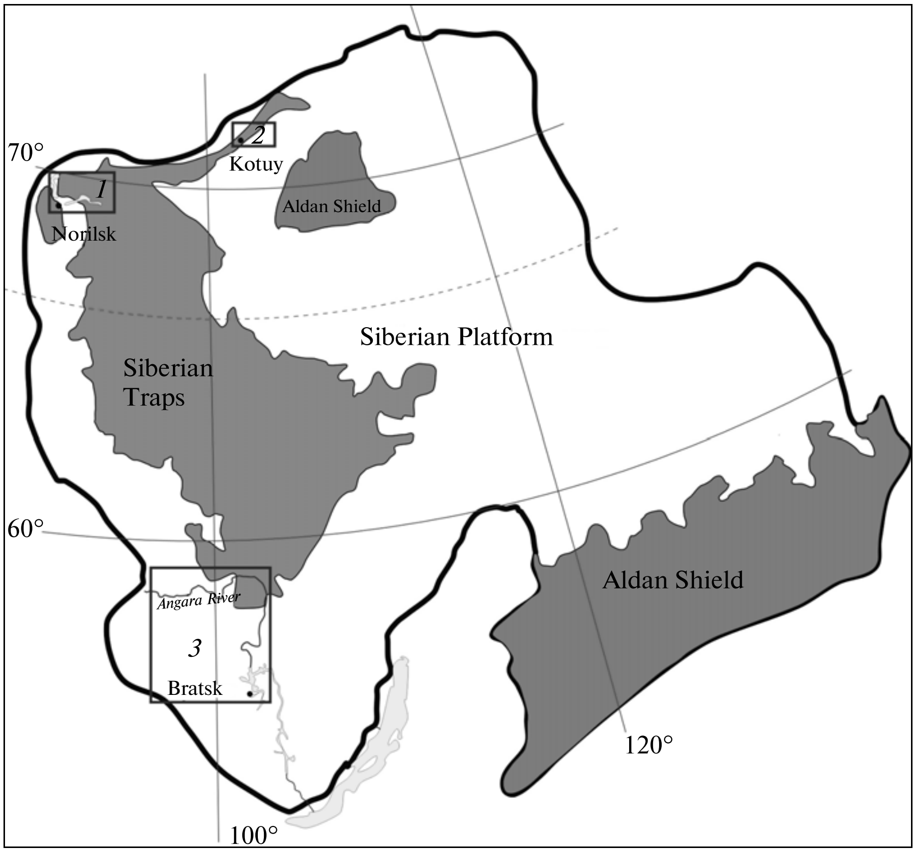

Fig. 1. The Siberian Trap Province. The layout of the studied regions: (*1*) Norilsk; (*2*) Kotuy; (*3*) Angara.

Formation (Domyshev, 1974).[1] By analyzing the palynocomplexes, Naumov and Ankudimova (1995) classified the tuffaceous sequences in this region as a separate Kapaevsky Formation of Korvunchansky Series. The rocks of this series show significant facial variability; the most complete sections of the tuffaceous strata are known within the iron ore deposits of the Angara-Ilim region (Naumov and Ankudimova, 1995). The thickness of the tuffaceous formations in the Angara River valley ranges from 50 to 300 meters. Compared to the other regions of the Tunguska syncline, the tuffaceous formations in this area feature higher facial variability, a significant share of xenogenic material in the composition of lithoclasts with single fragments of the Paleozoic sedimentary rocks up to 2–3 m in size, and steep tectonic contacts with the underlying sedimentary complex, often with dolerite intrusions and high displacement amplitudes (Domyshev, 1974). According to the explanatory notes to the sheets of the 1 : 200000 State Geological Map[1], the age of the tuffaceous sediments of the Angara River valley was established as the Early Triassic by analogy to the Korvunchansky Formation in the central part of the Tunguska syncline. On the other hand, according to the analysis of the palynocomplexes (Naumov and Ankudimova, 1995), the tuffaceous sequences were dated to the Tatarian age of the Upper Permian, in contrast to the Early Triassic strata of the Korvunchansky Formation in the central part of the Tunguska Syncline.

Further, the tuffaceous strata of Angara region will be referred to as the Kapaevsky Formation, as suggested in (Naumov and Ankudimova, 1995), in order to distinguish the studied rocks from the Korvunchansky Formation, which is widespread throughout the Tunguska Syncline.

Along its periphery, the field of volcanic rocks of the Tunguska Syncline is framed by a wide belt of dolerite sills, which mainly outcrop in the margins of the Angara-Taseeva depression. Based on the field observations and analysis of the borehole sections, six large dolerite sills intruded in different horizons of the Paleozoic deposits are distinguished (Feoktistov, 1976): Usol'sky, Zayarsky, Tulunsky, Tolstomysovsky, Padunsky, and Chuna-Biryusinsky (Fig. 2). From the west to the east, all these sills rise to increasingly higher strati-

[1] Explanatory Note to the 0–48–VII Sheet of the 1 : 200000 Geological Map of the USSR (Moscow. 1980). Explanatory Note to the 0–48–XIII Sheet of the 1 : 200000 Geological Map of the USSR (Moscow: Nedra, 1967).

graphic positions, which indicates that the magma intruded from the west eastwards (Fig. 3). It is assumed that the local source zone was located in the western part of the Angara-Taseeva depression, and the sills spanned up to 500 km (Feoktistov, 1976).

The lowermost Usolsky sill is located in the Lower Cambrian deposits. It gradually passes to the higher stratigraphic horizons and pinches out from the west eastwards. The average thickness of the sill is about 100 m, and its extent from the west to east is above 400 km. The Usolsky sill is not exposed on the surface; however, the Zayarsky sill, which is probably associated with the Usolsky sill, outcrops in the interfluve of the Angara and Ilim rivers (Feoktistov, 1976; Feoktistov, 1978). The Zayarsky sill is intruded in the Lower Cambrian deposits 200–600 m stratigraphically higher than the Usolsky sill.

The Tulunsky sill is embedded in the Upper Cambrian–Lower Ordovician rocks. It stratigraphically rises eastwards and outcrops in the Oka and Iya interfluve. The Tulunsky sill has a thickness of 90 m and stretches by up to 300 km in the northwestern direction (Feoktistov, 1976).

The Padunsky sill is exposed in the western part of the Irkutsk amphitheater, near the boundary with the Sayan region, as well as in the southern and eastern periphery of the Angara-Taseeva basin up to the town of Bratsk. In the central part of the Angara-Taseeva basin, the Padunsky sill occurs in the Lower Ordovician deposits. Farther eastwards, it gradually rises to the overlying stratigraphic horizons. In the basins of the Katanga, Nepa, Angara and Chuna rivers, the Padunsky sill branches, according to the generally accepted standpoint (Feoktistov, 1976; Naumov and Ankudimova, 1995; Ivanov et al., 2009). The Tolstomysovsky sill, which is considered as a lower offshoot of the Padunsky sill (Feoktistov, 1976), outcrops in the region of the town of Ust-Ilimsk and to the east of the Angara River, where it intrudes the tuff deposits of the Kapaevsky Formation (Naumov and Ankudimova, 1995) or the Tutonchansky and Korvunchansky formations (Domyshev, 1974). The upper sill is significantly eroded and only exposed in the basin of the Nepa River. The Padunsky and Tolstomysovsky sills extend over more than 200 km and their thickness attains 250 m (Feoktistov, 1978; Ivanov et al., 2008).

The Chuna-Biryusinsky sill penetrates the Upper Ordovician–Silurian layers; it is observed as separate outliers in the interfluve of the Angara and Biryusa rivers. According to (Naumov and Ankudimova, 1995), this sill is an offshoot of the Padunsky sill.

The age datings for the sills are contradictory. The direct transecting contacts between the different sills and other geological evidence of their age relationships are not known. However, the Padunsky, Tolstomysovsky, and Chuna-Biryusinsky sills are intruded by numerous diatrems, which control the iron ore deposits in the Angara-Ilim region. According to one hypothesis (Feoktistov, 1978), these explosion pipes are comagmatic with the Usol'sky sill. According to this, it is suggested that the Usolsky sill is the youngest. However, in the opinion of Naumov and Ankudimova (1995), the pipes are coeval with the Kapaevsky Formation. In the quoted paper, it is hypothesized that the Kapaevsky deposits and the Padunsky sill, whose outshoots, in the opinion of these authors, are the Tolstomysovsky and Chuna-Biryusinsky sills, were formed synchronously.

The existing isotopic datings are also contradictory. On the basis of numerous K-Ar age determinations, Feoktistov (1976) distinguished three phases in the trap magma intrusion within the Angara-Taseeva complex: (1) the Chuna-Biryusinsky sill; (2) the Padunsky and Tolstomysovsky sills; and (3) the Tulunsky and Usolsky sills. According to this hypothesis, at the earlier stages of trap magmatism, the sills intruded into the upper stratigraphic horizons; and at the later stages, they penetrated the lower layers of the sedimentary cover. The scatter of the obtained K-Ar age datings spans almost 100 Ma (265–179 Ma). Recently, a set of more reliable radiological Ar/Ar and U-Pb data was obtained for the sills of the Angara-Taseeva basin (Table 1). By analyzing their age distribution, Ivanov et al. (2013) identified two stages in the intrusive magmatism in the Angara-Taseeva basin: (1) Late Permian to the beginning of the Early Triassic (255–249 Ma) and (2) the end of the Early Triassic to Middle Triassic (244–239 Ma). We note that the isotope data obtained for the Padunsky, Tolstomysovsky, and Usolsky sills correspond to both the first and the second stages. It is also interesting that all the U-Pb datings range within 254–249 Ma, while most of the $^{40}Ar/^{39}Ar$ age determinations fall in the interval from 244 to 239 Ma, except for the single dating obtained for the Tolstomysovsky sill (255.8 ± 4.7/5.3 Ma) (Ivanov et al., 2013).

THE PROCEDURE OF THE STUDY

During the field works in 2010 and 2011, we collected paleomagnetic samples from the Tolstomysovsky, Padunsky and Tulunsky sills, as well as the basaltic tuffs of the Kapaevsky Formation, thin dolerite dikes, and Paleozoic sedimentary strata. More than 60 paleomagnetic sites were tested overall. From each site, from 8 to 30 samples oriented by a mining compass with control of the probable influence of strongly magnetic rocks on the magnetic needle of the compass were selected. The total number of the paleomagnetic samples is more than 600. The laboratory paleomagnetic studies were conducted according to the standard procedures (Zijderveld, 1967; Khramov et al., 1982; Shipunov, 1999) in the Petromagnetic Laboratory at the Faculty of Geology of Moscow State University, and in the Laboratory of the Main Geomagnetic Field and Rock Magnetism of Institute of Physics of the Earth, Russian Academy of Sciences (IPE RAS). All samples were subjected to the detailed ther-

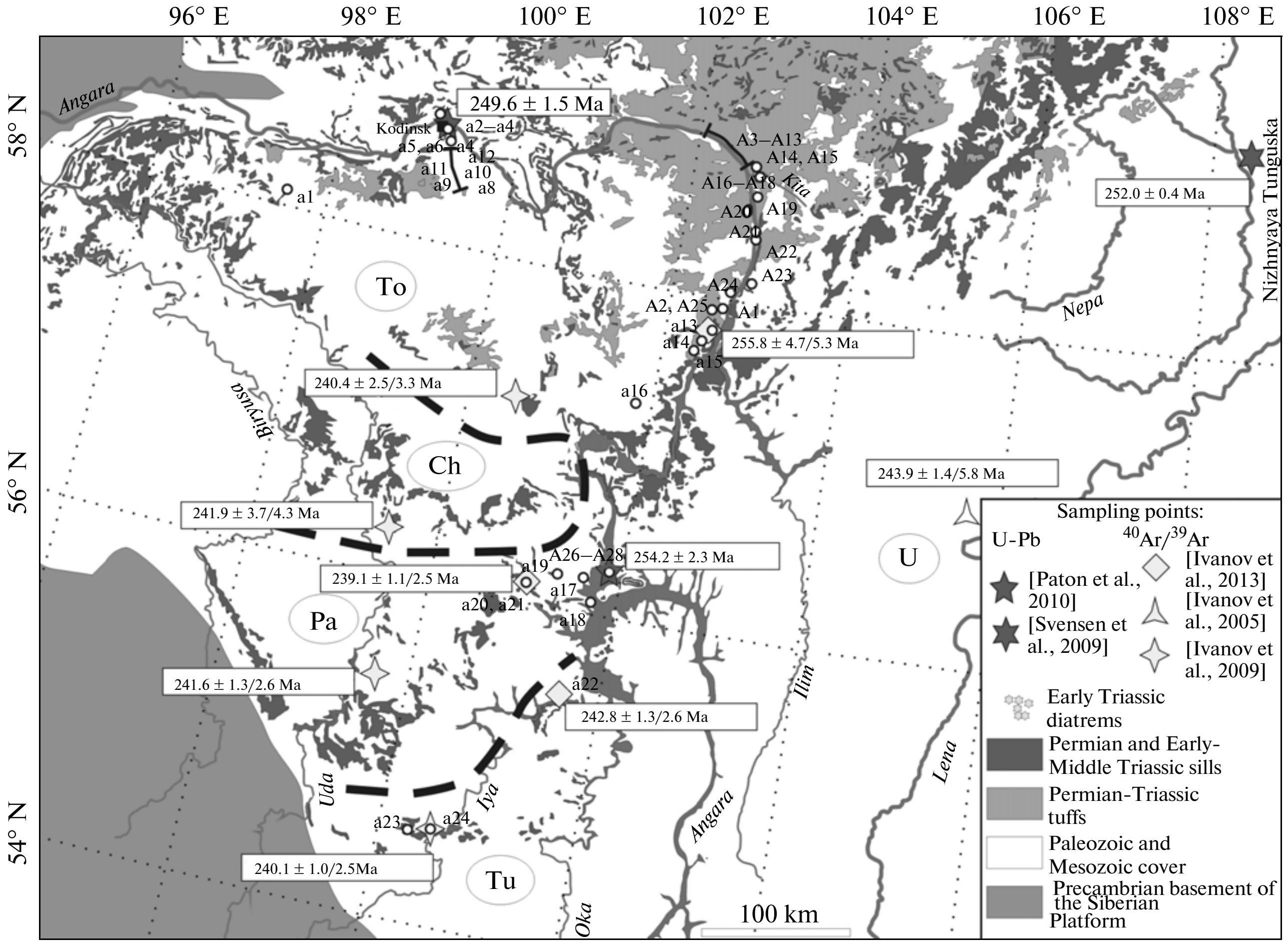

Fig. 2. The geological map of the studied area (after (Ivanov et al., 2013; Feoktistov, 1976) and the locations of the paleomagnetic sites. Dolerite sills: U, Usol'sky; Tu, Tulunsky; Pa, Padunsky; To, Tolstomysovsky; Ch, Chuna-Biryusinsky.

mal magnetic treatment mostly up to 580–600°C. The demagnetization included 12–15 steps. In order to demagnetize the samples, we used nonmagnetic furnaces with an uncompensated magnetic field of at most 5–10 nT. The remanent magnetization of the samples was measured by the JR-6 (AGICO) spinner magnetometers. The remanent magnetization measurements were processed by Enkin's program (Enkin, 1994) and the Remasoft program package (Chadima et al., 2006), which use the PCA method for isolating the magnetization components (Kirschvink, 1980). The parameters of the secular variation were calculated by the program package developed by Tauxe (2010). The paleomagnetic directions were combined in the directional groups by the reversal test (McFadden and McElhinny, 1990). In the calculations of the angular distances between the paleomagnetic poles, the uncertainties were taken into account by the model (Debiche and Watson, 1995).

THE RESULTS OF THE PALEOMAGNETIC STUDY

Most trap samples have preserved clear paleomagnetic signals. In most cases, the thermal treatment reveals two components of natural remanent magnetization. The low-temperature component, which is removed by heating up to 250–320°C, has the paleomagnetic direction close to that of the present magnetic field, which suggests its recent age and viscous origin. The high-temperature characteristic component is removed in the temperature range of 400–600°C (Fig. 4). The directional distribution of the characteristic component on the site level is presented in Table 2.

The Ordovician rocks sampled in the region of the town of Kodinsk at two sites about 0.5 and 1.5 km from the sill carry a high-temperature component with directions close to those expected for the Ordovician deposits of the Siberian Platform (Pavlov et al., 2012) and different from the directions of the trap component. The high-temperature component is demagne-

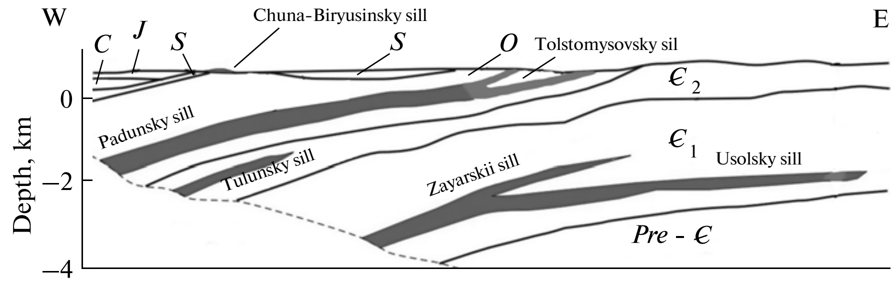

Fig.3. The schematic section across the Angara–Taseeva basin according to (Ivanov et al., 2009).

tized in the temperature range of 500–705°C. The low-temperature component is also present. In the site that is close to the contact with the sill, this component is removed at 450–530°C and has the paleomagnetic directions of the traps; in the site that is farther from the sill boundary, it is removed at 400–500°C and has a paleomagnetic direction close to the current direction. Thus, we observe the trap remagnetizing component close to the sill and its absence at a distance of 1.5 km from the sill, with the paleomagnetic directions of the host rocks and traps being different. This relationship between the magnetization components corresponds to the positive baked contact test and suggests that there was no regional remagnetization of the post-trap age in the studied region. This conclusion is supported by the absence of the signs of the trap component in the Ordovician rock sequence in the Rozhkova River, located in the Angara River basin a few dozen kilometers higher up the river after the Kodinsk dam within the area of the Tolstomysovsky sill (Pavlov et al., 2012).

DISCUSSION OF THE RESULTS

Grouping of Paleomagnetic Directions

By analyzing the site distributions of the average paleomagnetic directions, we identified three representative groups of the sites having statistically indistinguishable directions within the group and several separate sites whose directions significantly differ from the adjacent sites (Table 2). When grouping the sites, we took into account their geographical locations and their position in the geological structure of the region (Fig. 2). The first group includes the sites sampled from the Tolstomysovsky sill in the region of Kodinsk, in the Angara River basin from Ust-Ilimsk to the mouth of the Kata River, and from the tuffs of the Kapaevsky Formation and small dikes intruding them in the Kata River mouth. Overall, the first group includes 36 sites along the Angara River with a distance between the extreme sites of more than 200 km. The second group of the sites corresponds to the Padunsky sill and includes six sites in the region of the town of Bratsk and of the village of Vikhorevka. The third group (10 sites near the town of Tulunsky and the village of Klyuchi-Bulak) corresponds to the Tulunsky

Table 1. The isotope age dating of the sills of the Angara-Taseeva Basin

Object	Method	Age, Ma	Source	Site
Chuna-Biryusinsky sill	$^{40}Ar/^{39}Ar$	241.9 ± 3.7/4.3	Ivanov et al., 2009	–
Padunsky sill	U-Pb	254.2 ± 2.3	Paton et al., 2010	A26–A28
Padunsky sill	$^{40}Ar/^{39}Ar$	241.6 ± 1.3/2.6	Ivanov et al., 2009	–
Padunsky sill	$^{40}Ar/^{39}Ar$	239.1 ± 1.1/2.5	Ivanov et al., 2013	a21
Tolstomysovsky sill	U-Pb	249.6 ± 1.5	Paton et al., 2010	a7
Tolstomysovsky sill	$^{40}Ar/^{39}Ar$	255.8 ± 4.7/5.3	Ivanov et al., 2013	a13
Tolstomysovsky sill	$^{40}Ar/^{39}Ar$	240.4 ± 2.5/3.3	Ivanov et al., 2009	–
Tulunsky sill	$^{40}Ar/^{39}Ar$	242.8 ± 1.3/2.6	Ivanov et al., 2013	a22
Tulunsky sill	$^{40}Ar/^{39}Ar$	240.1 ± 1.0/2.5	Ivanov et al., 2009	a24
Usol'sky sill	U-Pb	252.0 ± 0.4	Svensen et al., 2009	–
Usol'sky sill	$^{40}Ar/^{39}Ar$	243.9 ± 1.4/5.8	Ivanov et al., 2005	–

Due to inaccuracy of the assumed decay constants of K-40, the $^{40}Ar/^{39}Ar$ datings are consistently younger than the corresponding U/Pb datings by 0.9%. Correspondingly, for direct correlation of the ages determined by different dating methods, the $^{40}Ar/^{39}Ar$ datings should be corrected by adding ~2.3 Ma (see (Paton et al., 2010; Ivanov et al., 2013) and references therein).

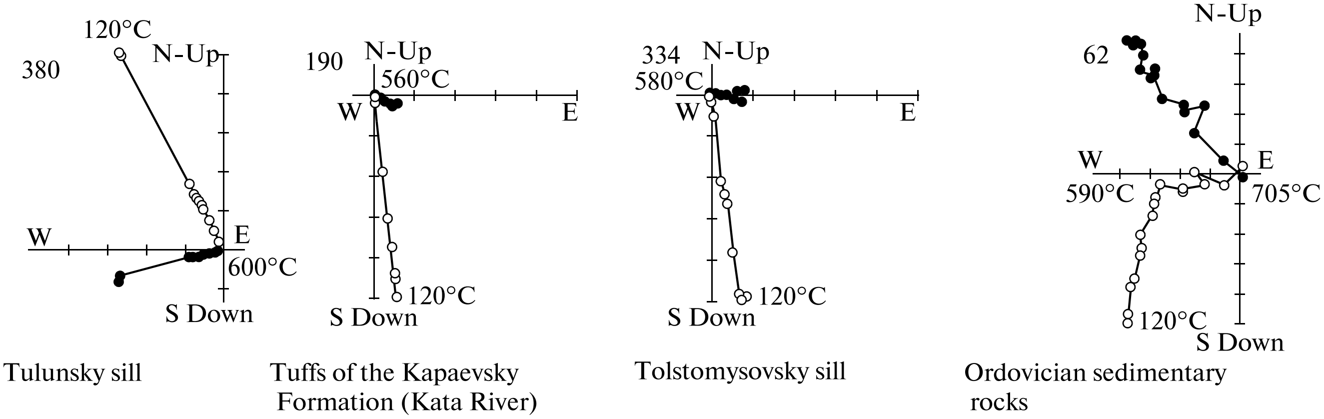

Fig. 4. The typical Zijderveld diagrams for the studied objects.

sill. All the samples of the first group (the Tolstomysovsky sill) have normal magnetic polarity, while the samples of the second and third groups (the Padunsky and Tulunsky sills) are magnetized reversely. The different polarity of the rocks from the Tolstomysovsky and Padunsky sills contradicts the existing ideas of their synchronous formation (Feoktistov, 1978). Some sites (Table 2) were not attributed to any group because their paleomagnetic directions significantly differ from those at the adjacent sites.

The average poles calculated for the Tulunsky, Padunsky and Tolstomysovsky sills, together with the tuffs of the Kapaevsky Formation and small dikes in the region of the Kata river mouth, significantly differ, and their confidence ellipses do not overlap (Fig. 5a). This indicates that the three identified sites correspond to three magmatic events that occurred at different times and resulted in the intrusion of large dolerite sills and, in the case of the first group, in the intrusion of the Tolstomysovsky sill with the simultaneous ejection of the tuffs of the Kapaevsky Formation. It cannot be ruled out that the host rocks, including the tuffs of the Kapaevsky Formation, could have been remagnetized during the intrusion of the large Tolstomysovsky sill. However, the absence of the trap directions in the Ordovician deposits at the *a6* site and in the Rozhkova section (Pavlov et al., 2012) indicates that there was no regional heating of the territory, which is required for the total remagnetization of the tuffs within the sampled area (about 2000 km^2).

The scatter in the virtual geomagnetic poles calculated for the group-forming sites is significantly lower for all the three groups than the secular variation estimated by the model (Tauxe and Kent, 2004) (Fig. 6). This suggests that the time taken by the formation of the Tolstomysovsky, Padunsky, and Tulunsky sills is insufficient for averaging the secular variation; i.e., these sills were formed within at most 10–100 ka (Tauxe, 2010). In addition, had the secular variation been averaged during the formation of any sill, we could reasonably expect the average pole of this sill to coincide with the paleomagnetic pole of the Siberian platform at the Permian-Triassic boundary. The difference of the average poles for the Tulunsky and Tolstomysovsky sills from the Permo-Triassic trap NMK pole for the Siberian platform at the Permian-Triassic boundary (Pavlov et al., 2011) provides an additional argument for the secular variation having not been averaged in these sills.

We note that the confidence ellipses for the poles of the Padunsky sill and the expected pole for the Siberian platform overlap (Fig. 5a), which is however insufficient for assuming that the secular variation in the rocks of the Padunsky sill have been averaged. At the same time, the average pole calculated from three sills is close to the NMK pole of the Siberian Platform (Pavlov et al., 2011). However, the confidence ellipse $\alpha95$ is too large (29.3°) to be used, for example, for paleotectonic reconstructions. In the calculations of the average pole from three sills and the sites with individual directions, which are not included in the identified directional groups (with equal weights of all objects), the confidence ellipses of the NMK pole and the resulting pole overlap. Here, $\alpha95$ for the calculated pole is noticeably lower (10.7°) than in the previous case (Fig. 5b), whereas the scatter in the virtual geomagnetic poles S agrees with the model (Tauxe and Kent, 2004). The latter presents an argument for the secular variation having been averaged during the time span of the formation of all the studied intrusive bodies and tuff strata. This gives us grounds to suggest that three large short magmatic events, which resulted in the formation of dolerite sills, occurred against the background of longer lasting and less intense magmatic activity, which led to the formation of magmatic objects having their individual paleomagnetic directions. The small intrusive bodies, which were wrongly related to the Tolstomysovsky or Padunsky sills, can

Table 2. The paleomagnetic directions for the sites and the average poles for the identified groups (n is the number of the samples in the site; N is the number of the sites used for calculating the average pole)

1. Tolstomysovsky sill					
Sill near the Kodinsk dam, lat = 58°42–43′, long = 99.9°–11′ (Tolstomysovsky sill)					
Site	n/N	D	I	K	a95
a2	13	52.4	80.5	216.3	2.8
a3	12	24.7	83.7	163	3.4
a4	13	64.8	85.3	171.8	3.2
a7-1	5	51.8	83.2	262.4	4.7
a7-2	6	31.1	83.7	108.8	6.5
a7-3	6	56.9	80.8	141.2	5.7
a7-4	6	60.3	82	269	4.1
a7-5	6	43.1	82.7	209.8	4.6
average	**8**	**48.7**	**82.9**	**1237**	**1.6**
Pole: Plat = 65.8, Plong = 125.5, A95 = 3.1					
Sills and dykes in the Kata River mouth, lat 58°44–54′, long = 102°17–41′					
A11	16	147.2	80.4	193.3	4.0
A12+13	21	117.3	85.5	171.7	2.4
A16	8	117.8	86.4	165.9	4.3
A17	12	105.5	84.6	204.6	3
A18	10	123.2	83.3	363.5	2.5
A4	12	117.3	83.7	92.2	4.5
A19	24	94.8	86.5	87.2	3.2
A6	13	70.9	87.3	135.9	3.6
A8	13	101.6	84	162.0	3.3
average	**9**	**116.6**	**84.9**	**820.4**	**1.8**
Pole: Plat = 53.3, Plong = 117.7, A95 = 3.5					
Sill between Ust'-Ilimsk and the Kata River mouth, lat = 58°03–32′, long = 102°45′ (Tolstomysovsky sill)					
A20	17	117.5	85.6	103.2	3.5
A21	11	152.9	83.5	143.9	3.8
A22	8	21.9	84	112.4	5.2
A23	6	82.2	78.8	337.8	3.7
A24	12	133.6	86	198.1	3.1
average	**5**	**98.6**	**87.4**	**223.4**	**3.2**
Pole: Plat = 57.2, Plong = 112.2, A95 = 6.4					
Sill at the southern outskirts of Ust'-Ilimsk, lat = 57°59′, long = 102°38′ (Tolstomysovsky sill)					
A1	10	289.3	86.3	38.4	7.9
A2	12	15.2	88	60.8	5.6
A25-1	9	72.4	85.8	129.2	4.5
A25-2	5	281.8	86	150.1	6.3
A25-3	9	116.9	83.5	145.3	4.3
a13	12	126.2	86.2	73.1	5.1
a15	12	150.2	81.5	196.9	3.1
average	**7**	**125.6**	**88.2**	**250**	**3.8**

Table 2. (Contd.)

Pole:: Plat = 58.4, Plong = 107.5, A95 = 7.6					
Tuffs in the Kata River mouth, lat 58°48–56′, long = 102°07–39°					
A10	8	62.9	80.1	87.7	5.9
A14	10	110.1	84.9	71.7	5.7
A15	16	115.6	82.7	32.2	6.6
A3	13	77.3	78	60.2	5.4
A5	20	126.3	81.8	80.7	3.7
A7	13	142.7	84.9	59.8	5.4
A9B	12	76.9	86.3	92.4	4.5
A9T	10	124.5	82.5	130.1	4.3
average	**8**	**101.1**	**83.4**	**325.2**	**3.1**
Pole:: Plat = 54.2, Plong = 124.6, A95 = 6.0					
Average paleomagnetic direction for group 1: N = 5; D = 90.9; I = 85.9; K = 563.4; a95 = 3.2. Average pole for group 1: N = 5 Plat = 57.4, Plong = 117.1, A95 = 4.0 Average coordinates: long = 101.8; lat = 58.5					
2. Padunsky sill					
Sill in the area of the Bratsk dam and the Vikhorevka village, lat = 56°05–17′, long = 101°12–49′ (Padunsky sill)					
Site	*n*/*N*	D	I	K	a95
A26	11	277.2	–76.3	111.6	4.3
A27	10	255.6	–76.7	65.1	6.0
A28	9	255.1	–78.7	79.1	5.8
a18	12	282.2	–78.5	97.5	4.4
a21-1	8	280.6	–82	129.6	4.9
a21-2	6	263.7	–80.5	74.5	7.8
average	**6**	**268.6**	**–79**	**617**	**2.7**
Average pole for group 2: Plong = 136.8, Plat = 51.2, A95 = 5 Average coordinates: long = 101.5; lat = 56.2					
3. Tulunsky sill					
Sill near the Klyuchi-Bulak village and town of Tulun, lat = 55°31–35′, long 100°35′–101°42′ (Tulunsky sill)					
Site	*n*/*N*	D	I	K	a95
a22-2	5	259.4	–59.2	93.6	8
a22-3	5	260.7	–61.8	392.8	3.9
a22-4	6	287.6	–71.3	110.2	6.4
a23-1	10	286.4	–66.8	21	10.8
a23-2	10	280.3	–62	100.7	4.8
a24-1	6	253.8	–47.2	48.5	9.7
a24-2	6	246.7	–62.4	77.6	7.7
a24-3	6	250.3	–65.9	110.2	6.4
a24-4	6	263.1	–63	177.1	5
average	**10**	**261.4**	**–63.0**	**72.0**	**5.7**

Table 2. (Contd.)

Average pole for group 3: Plat = 39.7, Plong = 167.0, A95 = 7.9 Average coordinates: long = 100.6; lat = 55.6					
Average pole for three groups (Tolstomysovsky, Padunsky, and Tulunsky sills): Plat = 51.3, Plong = 143.3, A95 = 28.9					
Lower Ordovician sedimentary rocks from two outcrops near the boundary of the Tolstomysovsky sill in the area of the Kodinsk dam a5+6					
Site	*n*/*N*	*D*	*I*	*K*	a95
a5-6					
High-temperature component	12	328.0	33.6	12.9	12.6
Low-temperature trap component (nearest site to the sill)	8	50.2	86.3	106.0	5.4
Low-temperature recent component (remote site)	6	336.4	68.3	27.8	12.9
Individual directions for the sites, which are not related to any group					
Sill on the Boguchany-Krasnoyarsk road					
Site	*n*/*N*	*D*	*I*	*K*	a95
a1 59°10′ N, 97°23′ E	14	255.2	–64.6	81.7	4.4
Sill on the Kodinsk-Bratsk road					
a8 59°10′ N, 97°23′ E	10	165.2	84.3	214.5	3.3
a9 58°24′ N, 99°17′ E	10	119.1	63.6	68.9	5.9
a10 58°34′ N, 99°10′ E	8	46.6	–83.1	146.5	4,6
a11 58°35′ N, 99°10′ E	9	40.6	82.1	137.1	4.4
a12 58°40′ N, 99°09′ E	4	286.5	–69.0	165.3	7.2
Sills and tuffs on the Ust'-Ilimsk—Bratsk road					
a14 (tuffs) 57°46′ N, 102°25′ E	14	223.4	–80.3	216.4	2.7
a16 57°11′ N, 101°51′ E	12	233.8	–79.3	49.3	6.9
Sills in the region of the town of Bratsk and Vikhorevka villag					
a19	11	318.3	–77.8	107.8	4.4
a20	9	137.9	–79.5	124	4.6
Average pole for all objects: Plat = 51.4, Plong = 133.1, A95 = 11.7					

probably present such objects. In addition, along with the tuff layers, which were formed simultaneously with the Tolstomysovsky sill, the rocks in the Angara region also contain smaller amounts of the products effused by the eruptions that were not synchronous with the main volcanic stage (tuffs in the Badarma River valley, site 14).

Comparison with the Geochronological Data

A number of the sites were sampled at the points of acquiring the collection for geochronological dating (see Table 1 and Fig. 2). The obtained results allow us to paleomagnetically validate the existence of two peaks in the magmatic activity, which were conjectured by Ivanov et al. (2013) from the analysis of isoto-

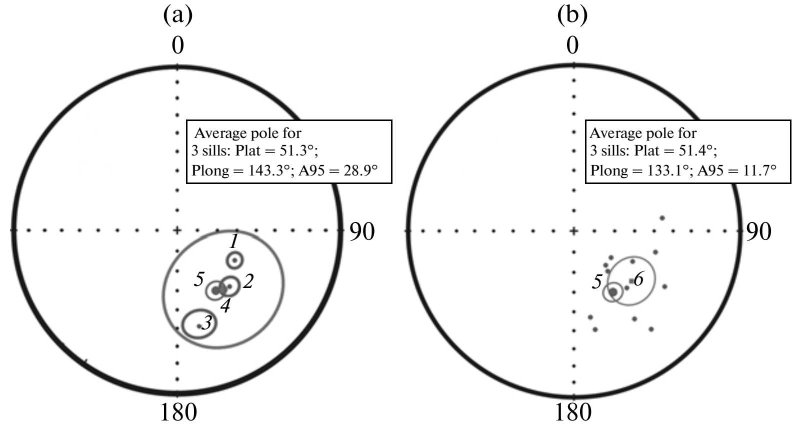

Fig. 5. (a) The average poles for the sills: (*1*) Tolstomysovsky; (*2*) Padunsky; (*3*) Tulunsky; and (*4*) the average pole for three sills. The comparison of the average pole of the sills with the (*5*) Permian-Triassic NMK paleomagnetic pole in the Siberian Platform (Pavlov et al., 2011); (b) the comparison of the (*5*) NMK pole with the (*6*) average pole for all the studied objects: 1) poles (*5*) and (*6*) are close; 2) α95 is less than in the case (a).

pic datings. For example, the samples from sites a22 and a24 (Tulunsky sill) have very similar paleomagnetic directions, which suggests that the dolerites at these points were formed simultaneously. This does not contradict the $^{40}Ar/^{39}Ar$ datings at these sites, whose confidence intervals overlap (242.8 ± 1.3/2.6 Ma according to (Ivanov et al., 2013) and 240.1 ± 1.0/2.5 Ma according to (Ivanov et al., 2009), respectively). Sites a7 and a13 located within the Tolstomysovsky sill also have close paleomagnetic directions and isotopic age datings with the overlapping confidence intervals (249.6 ± 1.5 Ma according to (Paton et al., 2010) and 255.8 ± 4.7/5.3 Ma according to (Ivanov et al., 2013), respectively). The tuffs of the Kapaevsky Formation and small subvolcanic bodies, which are probably comagmatic with them and have close paleomagnetic directions at seven sites in the Kata river mouth, also belong to this directional group. In this case, the Late Permian age of the Kapaevsky Formation estimated by the palynological analysis (Naumov and Ankudimova, 1995) contradicts the age of 249.6 ± 1.5 Ma (Paton et al., 2010), which is younger than the Permian-Triassic boundary of 252.6 ± 0.2 Ma (Metcalfe and Isozaki, 2009). Taking into account the inconsistency of the paleontological and geochronological data, we estimate the probable age interval of the magmatic event corresponding to the selected directional group 1 (Tolstomysovsky sill) as the end of the Late Permian to the beginning of the Early Triassic. The probable duration of the event is 10–100 ka at most, since the secular variation has not been averaged. We note that there is a different $^{40}Ar/^{39}Ar$ age dating for the Tolstomysovsky sill, which dates this event to Middle Triassic (240.4 ± 2.5/3.3 Ma) (Ivanov et al., 2009). One of the possible explanations for this is that the dated rocks were related to the Tolstomysovsky sill by mistake.

The paleomagnetic results for the Padunsky sill were obtained from the sites with significantly different isotopic ages: 254.2 ± 2.3 Ma (Paton et al, 2010; site A26–A28; U-Pb dating) and 239.1 ± 1.1/2.5 Ma (Ivanov et al., 2013; site a21; $^{40}Ar/^{39}Ar$ age). However, the average paleomagnetic directions in the corresponding sites are statistically indistinguishable, which indicates that they are coeval. There are two ways to explain this: (1) at least one of the available age datings does not reflect the time of the formation of the sill or (2) the Late Permian rocks from site A26–A28 have been remagnetized during the intrusion of the younger Middle Triassic dolerites (site a21), which required heating above 600°C. However, the statistically insignificant but still noticeable difference in the average paleomagnetic directions at sites A26–A28 and a21 testifies to the primary magnetization, since in the case of remagnetization, the paleomagnetic directions should be close to each other within the determination error.

Comparison with the Data from the Norilsk and Maymecha-Kotuy Trap Provinces

In order to correlate the magmatic events that occurred in the Angara-Taseeva basin to those in the north of the Siberian Platform, we compared the average poles calculated for the Tolstomysovsky, Padunsky, and Tulunsky sills with those calculated for the volcanic pulses recorded in the lava sections of the Norilsk and Maymecha-Kotuy regions (Pavlov et al., 2011). The calculations of the angular difference (Table 3) show that the average pole for the Tolstomysovsky sill is statistically indistinguishable from the poles of the three volcanic pulses from the Kotuy section (P4, P8, and P9; Arydzhangsky Formation). Across the entire Norilsk lava section (Sunduk-Ikon-Abagalakh), the Tolstomysovsky sill has an insignificant angular difference only with the P13 pulse, which includes the lava flows of the Morongovsky Formation. The proximity of the poles indicates that the Tolstomysovsky sill could have been formed simultaneously with any of the mentioned volcanic pulses; however, it should be taken into account that a pole could have occurred at the same location at a different time. Nevertheless, the U-Pb age obtained from the Tolstomysovsky sill (249.6 ± 1.5 Ma) (Paton et al., 2010) overlaps with the dating for the Norilsk-1 intrusive, which is considered to be coeval with the Morongovsky Formation (251.2 ± 0.3 Ma; U-Pb age) (Kamo et al., 2003), and close to the dating for the Arydzhangsky Formation (251.7 ± 0.4 Ma; U-Pb age) (Kamo et al., 2003). This indicates that these units were formed simultaneously. In addition, according to the correlation scheme of the effusive traps of the Maymecha-Kotuy and Norilsk regions, [2] the Arydzhangsky Formation is correlated to the Morongovsky-Mokulaevsky horizon. All this supports arguments for correlating the Tolstomysovsky sill and its comagmatic Kapaevsky Formation to the Morongovsky Formation in the Norilsk section and to the Arydzhangsky Formation in the Kotuy section, as well as for correlating the Early Triassic deposits of the Kapaevsky Formation to the Tolstomysovsky sill.

The Padunsky sill has statistically indistinguishable poles with two volcanic pulses in the Kotuy river section (P11 and P14 in the Onkuchaksky Formation). Due to the absence of the reversely magnetized pulses in the Noril'sk lava section, the Padunsky sill is difficult to correlate to the most part of the Norilsk section. The only exception is the Ivakinsky Formation; however, the angular difference between the poles of the reversely magnetized pulses of the Ivakinsky Formation and the poles of the Padunsky sill is too high. The existing U-Pb age dating for the Padunsky sill (Paton et al., 2010) within the confidence intervals falls in the interval between the U-Pb ages for the Arydzhangsky and Delkansky formations in the Maymecha-Kotuy region (Kamo et al., 2003) and, therefore, does not contradict the probable synchronous formation of the Padunsky sill and Onkuchaksky rocks. On the other hand, if we take into account that the poles with different ages could have probably coincided in space, it is also possible that the proximity of the poles of the Padunsky sill and the pulses of the Onkuchaksky Formation is the result of mere chance. Therefore, our data do not completely rule out the possibility that the Padunsky sill has the Middle Triassic age, as established by the $^{40}Ar/^{39}Ar$ method (Ivanov et al., 2009; Ivanov et al., 2013).

The Tulunsky sill has statistically indistinguishable poles with the P12 pulse of the Onkuchaksky Formation in the Kotuy River section and with the P1 pulse

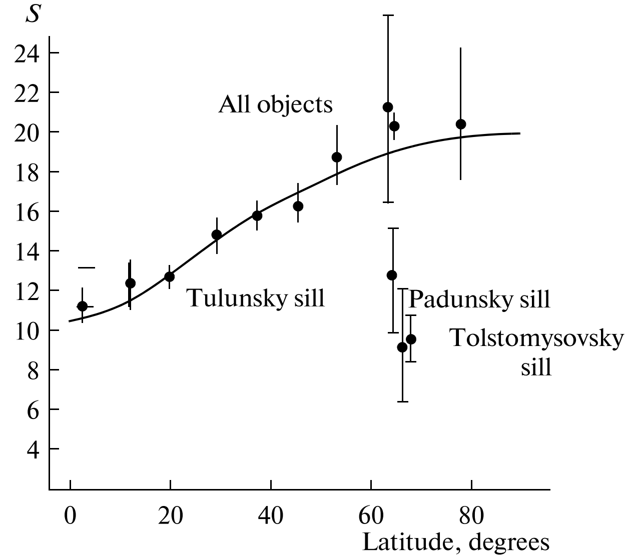

Fig. 6. The scatter of the virtual geomagnetic poles for the Padunsky, Tulunsky, and Tolstomysovsky sills and the average pole for all objects. The dependence of VGP scatter on latitude according to the model (McElhinny and McFadden, 1997; Tauxe and Kent, 2004).

of the Ivakinsky Formation in the Ergalakh section of the Norilsk region. We note that the scenario where all these three magmatic events are synchronous is excluded since, according to the paleontological data, the Ivakinsky Formation has the Late Permian age [3], and the Onkuchaksky Formation overlays the Arydzhangsky Formation, which is dated to Early Triassic, according to the paleontological and geochronological data (Ivanov, 1959; Kamo et al., 2003). This scenario also contradicts the mentioned correlation scheme of the effusive traps of the Maymecha-Kotuy and Norilsk regions, according to which, the Ivakinsky and Onkuchaksky Formations correspond to the different time levels. In addition, for the Tulunsky sill, there are only $^{40}Ar/^{39}Ar$ age datings, which estimate its age as Middle Triassic (Ivanov et al., 2013; Ivanov et al., 2009). This also contradicts the scheme of correlation of the Tulunsky sill to any pulses from the Norilsk and Maymecha-Kotuy regions, since neither the Ivakinsky nor the Onkuchaksky Formation can be dated to the Middle Triassic due to the Early Triassic age of the overlying layers (Kamo et al., 2003). Thus, the data obtained so far are insufficient for definitely preferring any of the probable variants of correlation of the Tulunsky sill to the traps of the North of the Siberian Platform.

[2] A.M. Fetisova, R.V. Veselovskiy, A.V. Latyshev, V.A. Rad'ko, and V.E. Pavlov, Magnetostratigraphy of Permian-Triassic traps of the Kotuy River basin in light of new paleomagnetic data, *Strat. Geol. Correlation* (in press).

[3] *Explanatory Note to the 1 : 1000000 State Geological Map of the Russian Federation (new series)*, Sheet R–45–47-Norilsk. St.-Petersburg:VSEGEI, 2000.

Table 3. The angular difference between the poles of the sills and the volcanic pulses identified in the lava sections of the Norilsk and Maymecha-Kotuy regions (Pavlov et al., 2011)

Sill		Tolstomysovsky sill	Padunsky sill	Tulunsky sill
Formation	Pulse			
Arydzhangsky Formation	P4	2.7° ± 6.1°		
	P8	5.4° ± 7.1°		
	P9	4.1° ± 8.5°		
Onkuchaksky Formation	P11		5.8 ± 8.4°	
	P12			5.0° ± 7.0°
	P14		2.7 ± 5.7°	
Ivakinsky Formation	P1E			6.2° ± 6.5°
Morongovsky Formation	P13	8.6° ± 10.1°		

CONCLUSIONS

The obtained paleomagnetic results together with the geological, geochronological and paleontological data suggest that the history of formation of Permian-Triassic traps in the southern part of the Siberian platform (Angara-Taseeva basin) included three large magmatic events, which occurred within a geologically short time interval. The first event was the intrusion of the Tolstomysovsky sill and eruption of the volcanic tuffs of Kapaevsky Formation in the region of Angara River near the Kata river mouth. The second event was the intrusion of the Padunsky sill; and the third event was the intrusion of the Tulunsky sill.

The existing paleomagnetic, geochronological, and paleontological data suggest the Early Triassic age for the Tolstomysovsky sill and Kapaevsky Formation. The formation time of the Padunsky sill is difficult to evaluate since its isotopic datings are contradictory. However, the idea of synchronous formation of the Padunsky and Tolstomysovsky sills is disproved by the different polarity of the average directions of the characteristic magnetization component. Our paleomagnetic results show that in the geological mapping of the Tolstomysovsky and Padunsky sills, the magmatic bodies having different ages were frequently related to the same sill. Moreover, some of the published radioisotope datings can be wrong. According to the isotopic dating, the intrusion of the Tulunsky sill occurred in the Middle Triassic, and our paleomagnetic data do not pose any additional constraints on the age of this event. These three short and strong bursts in the magmatic activity occurred against the background of the prolonged less intense magmatism, which resulted in the formation of small intrusive bodies and tuff units. The positions of the Usolsky and Chuna-Biryusinsky sills in this model are difficult to assess because of the lack of paleomagnetic data. It is probable that each of these sills corresponded to a separate peak in the magmatic activity.

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